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Assessment of variable coded symbology using visual search performance and eye fixation measures

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SUMMARY

Problem

Previous research has demonstrated that mixing color block-filled symbols (e.g., NATO, MIL-STD-2525A) with color-coded or monochrome line-drawn symbols (e.g., NTDS) can help to organize a tactical display for specific operator tasks and in some cases improve visual search for specific symbols. The goal of mixing symbol types, termed variable coded symbology (VCS), is to organize tactical displays for a particular task by having task relevant symbols coded in a more visually prominent manner than more irrelevant symbols. A recent visual search experiment found that one form of VCS (mixing recessed gray NTDS symbols with more prominent color-coded NTDS symbols) was associated with poor visual search performance and negative user opinions. The present study replicated the visual search methodology and included eye tracking measures in an attempt to determine why particular VCS combinations produce inferior visual search performance.

Findings

The results replicated previous findings; the VCS scheme using subdued gray NTDS symbols in combination with color-coded NTDS symbols produced the poorest visual search performance. Confusion matrices for each display condition were constructed from eye fixation dwell times. These matrices indicated that gray and white symbols accounted for a disproportionate percentage of confusions across all display conditions.

Application

The use of recessed gray and prominent color-coded line-drawn (NTDS) symbols as a VCS tactical display is not advised. Combining color-coded NTDS symbols with prominent block-filled color NATO symbols is associated with faster visual search rates and fewer target/distractor confusions. Recessed gray NTDS symbols can be added to this latter display scheme provided they are in limited numbers and have limited task relevance.

ABSTRACT

Combining different tactical display symbols within a single display has been shown to be an effective way of organizing a display for particular command and control tasks. Previous results have shown that some variable coded symbol (VCS) combinations result in poorer visual search performance and negative user opinion data. The present study examined four different tactical display symbol schemes using a visual search procedure and simultaneous collection of eye fixation data. These conditions included a baseline condition composed of color-coded and line drawn NTDS symbols, a combination of recessed gray NTDS and color-coded NTDS symbols (VCS1), a combination of color-coded NTDS and block-filled, color-coded NATO symbols (VCS2), and a combination of all three of the aforementioned symbol types in one display (VCS3). Nine subjects completed a search and selection task containing four blocks and a total of 168 targets. The recessed gray NTDS symbols of the VCS1 scheme demonstrated the most prolonged search times, while search times were fastest for the color-filled NATO symbols of the VCS3 scheme. Target-distractor symbol confusions, as determined by fixation dwell times, were least evident in the VCS2 configuration. Gray and white symbols accounted for a disproportionate percentage of symbol confusions across all display conditions. The use of recessed gray and prominent color-coded line-drawn (NTDS) symbols as a VCS tactical display scheme is not recommended. Combining color-coded NTDS symbols with prominent block-filled color NATO symbols is associated with faster visual search rates and fewer target/distractor confusions.

INTRODUCTION

Enhanced radar sensitivity and the sharing of data among multiple combat systems has provided operators of military command and control consoles the ability to display hundreds of airborne, surface and subsurface tracks on a single tactical display. The use of color to code redundantly tactical symbol shape with various amity categories (e.g., unknown, neutral, friend, hostile) has helped to declutter and better organize these displays. The Naval Tactical Data System (NTDS) symbols used to portray tracks are generally square, round and diamond shaped, and are modified by presenting a partial representation of the symbol to identify airborne and subsurface tracks. Numerous studies had demonstrated the benefits, in terms of visual search efficiency, of using color in such displays (Christ, 1975; Davidoff, 1987; Jacobsen, Neri and Rodgers, 1985). Several studies have examined whether color-filled symbols are more discriminable than redundantly color-coded line drawn symbols (Nugent, Keating and Campbell, 1994; Van Orden, Osga and Lauben, 1991). The color filled symbols have been proposed as a North Atlantic Treaty Organization (NATO) maritime standard, and closely resemble the NTDS symbols in shape (NATO STANAG 1990). A Department of Defense standard (MIL-STD-2525A, 1996) also proposes color line drawn or color filled symbols for maritime tracks that retains many of the features of NATO and NTDS shapes.

In order to specify methods for decluttering tactical displays, Osga and Keating (1994) investigated the simultaneous display of multiple tactical symbol types on the same display. Their scheme, called Variable Coded Symbology (VCS), uses symbols from both the NTDS and NATO taxonomies. The general shape classes of the block-filled NATO symbols were always coded redundantly with color, while NTDS symbols appeared in either color-coded or monochrome representations. Eight experienced Navy combat information center (CIC) operators participated in the Osga and Keating study. The participants task was to construct VCS filters relevant to their typical CIC watchstanding duties by selecting from four basic symbol configurations (e.g., color-filled NATO, gray NTDS). Color-filled NATO symbols were used for coding the symbols of greatest importance to the participant, while gray NTDS symbols were used to code the symbols of least importance. Participants uniformly reported strong support for the VCS displays compared to existing display filtering methods, and found the VCS scheme to be a potentially important information management feature.

Using a visual search paradigm, Nugent (1996) examined the efficacy of symbols within the VCS scheme by comparing a standard non-VCS display condition with three variants of VCS coding. There were four display conditions using various configurations of symbols shown in Figure 1. The symbols were generally partial or entire renderings of circular, triangular, hexagonal or square shapes, in either NTDS or NATO format. NTDS symbols could be colored in gray, or redundantly coded with color (e.g., blue-circular, red-triangular, green-heagonal, white-square). Block-NATO symbols were always color-coded using the same convention as for the NTDS symbols. The four display schemes studied were:

Baseline:	all color-coded NTDS symbols,
VCS1:	color-coded NTDS symbols (prominent); gray NTDS symbols (recessed),
VCS2:	block-NATO symbols (prominent); color-coded NTDS symbols (recessed),

VCS3: block-NATO symbols (prominent); color-coded NTDS symbols (intermediate); gray NTDS symbols (recessed),

Participants searched for particular symbols (prompted by a probe stimulus) on static plots containing numerous symbols and types within each display configuration. They used a trackball to move a cursor and select targets (2 to 5 targets per trial), then pressed a key to indicate that they had completed the trial. Figure 1 is a portion of a display from the VCS3 condition, with all three symbol prominence levels present.

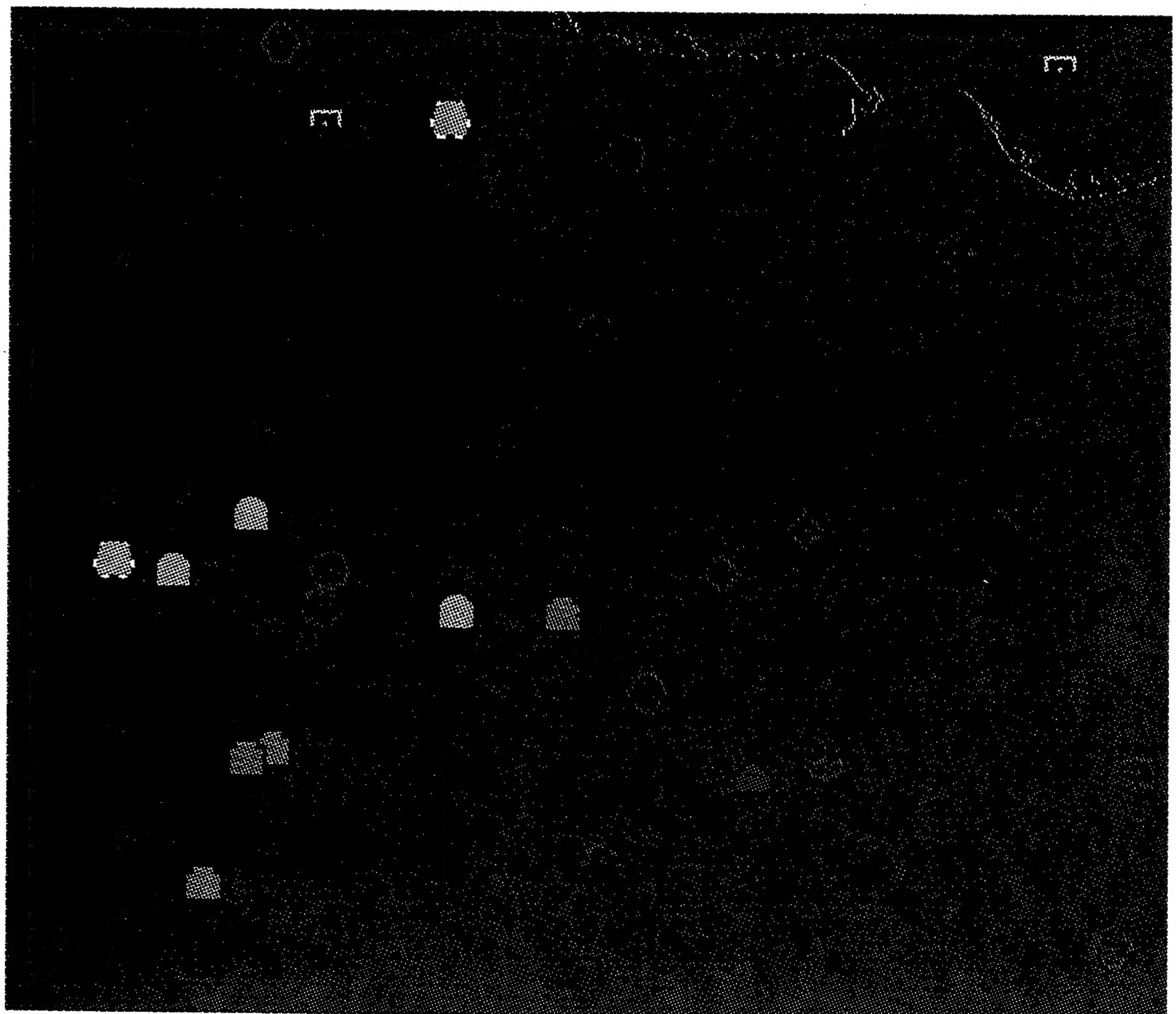


Figure 1. Portion of display from the VCS3 condition.

Using a throughput measure that integrated search times and error rates, Nugent (1996) found that search performance was poorest for the VCS1 condition in general, and particularly for the visually receeded symbols within that VCS scheme. Search performance was significantly better for the prominent symbols within the VCS3 configuration. Based upon these results, Nugent advised against the simultaneous use of color-coded and gray NTDS symbols exclusively in the same display. Nugent also collected user opinion data, and found that the VCS2 and VCS3

configurations were favored over the baseline and VCS1 schemes. Participants expressed negative opinions about the VCS1 method. Thus, Nugent's search efficiency data was in general agreement with the opinion data, and demonstrated that the VCS approach could enhance visual search efficiency within a more organized display.

Nugent's (1996) results are curious, however, because search rates varied significantly within VCS subcategories and were dependent upon which other subcategories were present. For example, VCS1 and VCS2 were present within the VCS3 configuration, yet the search rates within VCS1 and VCS2 were not similar to those observed for VCS3. The search rates for recessed symbols (gray-NTDS) within VCS1 were significantly lower than all other subcategories, even gray-NTDS symbols within VCS3. Similarly, prominent symbols in VCS3 (block-NATO) had the fastest search rates, even faster than identical symbols in VCS2. The obvious explanation for these results is that the number of symbols to be inspected declined as more symbol types were combined to form the VCS schemes. Throughput scores were lowest for the visually receded symbols in VCS1, and, in fact, these symbols were present in greater numbers than in the VCS3 scheme (eg., 57 and 47 gray-NTDS symbols, respectively). Likewise, throughput scores were highest for the visually prominent color-filed symbols of the VCS3 display, which contained 38 visually prominent color-NATO symbols, compared to 50-like symbols in the VCS2 configuration. However, Nugent's results could not be due entirely to changes in the number of sub-class symbols between VCS conditions, as throughput scores for color-NTDS symbols did not differ significantly despite sub-set sizes which varied from 33 to 98 symbols. Thus, while Nugent's results are very encouraging with respect to the higher throughput scores obtained for the VCS3 configuration, there are some unexplained effects. It is not clear, for example, whether the lower throughput scores associated with particular symbol sub-classes were due to generally inefficient search or due to specific confusions within or between symbol sub-classes.

The goal of the present study was to replicate and amplify upon Nugent (1996) by collecting eye tracking data in order to identify symbol types and combinations within the VCS configuations that might require modification to enhance discriminability. Eye tracking technology permits the collection visual scanning data that can be used as an index of visual search efficiency. For example, the number of fixations and the distance between them provides additional information with respect to the visual effort required to locate a target (Zelinsky and Sheinberg, 1997). Examination of fixation times for specific symbol classes would enable an analysis and assessment of confusibility between symbols within the different VCS displays.

METHOD

Participants: Nine participants (3 women and 6 men, mean age = 29.5 years) volunteered to participate in the study. None of the participants wore corrective lenses and all had normal color vision as assessed with psuedoisochromatic plates. They were paid $7.50 for each hour of participation.

Materials: An Apple Macintosh Quadra 840 computer was used to display stimuli and to record participant's responses. Stimuli were presented on a 19-inch diagonal Radius color

monitor. A 4 x 5 numeric entry keypad and a Rollermouse trackball with right-thumb operator selection key served as input devices. Eye activity was monitored using an Applied Sciences Laboratory SU4000 eye tracking system. The subject wore head-mounted optics (an infrared light source co-linearly aligned with a camera mounted above reflective glass), which fed into the image processing hardware of the system. The system calculated the location and diameter of the pupil reflection, and location of the corneal reflection at a sampling rate of 60 Hz. The eye tracking system was controlled by an 80486 PC computer. The eye tracking computer received synchronization signals from the stimulus computer for the alignment and merging of visual search performance and eye activity data sets.

Target and distractor stimuli were color and monochrome versions of the Naval Tactical Data System (NTDS) symbols and color filled North Atlantic Treaty Organization (NATO) Standard Agreement 4420 tactical symbols (NATO STANAG, 1990). The NATO symbols are similar in shape to the NTDS symbols, as shown in Figure 1. Target and distractor stimuli were represented in equal numbers of air (upper-half symbols) and sea surface (whole symbols) vehicular tracks in each of six amity categories (Unknown, Friend, Assumed Friend, Neutral, Suspect and Hostile). All symbols were displayed without amplifying alphanumeric or iconic elements in the center of the symbol frame.

There were four display conditions; a baseline condition and three variants of the VCS scheme. In the baseline condition all symbols were presented in the color-NTDS format, with circular symbols in blue, triangular symbols in red, square symbols in white, and hexagonal symbols in green. In VCS method 1 (VCS-1), color-coded NTDS symbols were combined with NTDS symbols coded in gray to construct a display of visually prominent and recessed items. VCS-2 consisted of color-coded block-NATO symbols and color-coded NTDS symbols. VCS-3 consisted of color-coded NATO, color-coded NTDS, and gray NTDS in an attempt to establish three layers of visual prominence.

Procedure: Participants were first tested for normal color vision using pseudoisochromatic plates. Next, they received instructions on console operating procedures. This was followed by three practice exercises to acquaint them with the first presentation method, and twelve experimental trials using that method. Each trial began with a probe symbol presented in the upper left of the display screen. The participant's task was to locate, select, then enter as many target symbols from the tactical display as matched the probe stimulus. A target symbol was hooked by pressing the hook button on the trackball, and entered by pressing the "Answer Select" button on the numeric keypad. The latter action resulted in the display of the selected symbol in a box located below the probe stimulus. Participants pressed the "Done" button on the keypad to signal the end of a trial, after which the computer advanced to the next item. A 30-sec time limit was imposed for completion of each trial. There were 12 trials each for the Baseline, VCS1 and VCS2 conditions. The VCS3 method contained 18 trials; the additional trials were included to assure an adaquate number of trials for each of the three symbology types used within the VCS3 scheme.

There were two static tactical plots for each of the four display configurations. There were an equal number of trials for each of the two plots. Baseline, VCS1 and VCS2 methods were randomly ordered for each participant. The VCS3 scheme was always presented last,

because Nugent (1996) had learned during pilot testing that it was much easier for subjects to interact with the three symbology types within the VCS method after having been exposed to paired combinations of the symbol sets in the other display configurations. Participants were always presented with three practice trials prior to the experimental trials across all four display conditions.

Scoring: Search time and accuracy data were recorded for every trial. Search time per target was calculated by dividing the total elapsed time from the presentation of the probe stimulus to the "Done" response, by the number of targets selected during the trial. This calculation was a purposeful departure from Nugent (1996) who used the time derived from the participants' pressing the "Select" button. Within traditional visual search paradigms used to study perceptual processes, participants typically make a "yes" or "no" response to the presence or absence of a target stimulus present within an array of distractor stimuli (Treisman, 1986). The time it takes to realize that a target is not present on a display is typically double the time it takes to determine that a target is present, but not always. There are stimulus configurations that produce target-absent search rates that are either much less than, or much greater than double the rate for target-present searches (e.g., McLeod, Driver, Dienes and Crisp, 1991). Essentially each trial within the present task can be considered as a set of target-present searches, followed by a target-absent search. Nugent's (1996) method makes the assumption that the time required to determine that no more targets exist on the display is a constant across symbol types. Using the "Done" time to calculate search time per target makes no such assumption. It could be argued that trials containing fewer targets would produce time per target data inflated by the target absent search to a greater extent than trials containing many targets. We contend, albeit without supporting data, that the time required for the target-absent portion of a trial declines as a function of the number of targets within a trial because of the greater opportunity to scan the display during the acquisition of target stimuli.

Raw point-of-regard (POR) eye data was processed by a space-by-time boundary fixation algorithm provided by the eye tracking system manufacturer. This algorithm derived fixations by first finding six successive x and y POR data points with a standard deviation of less than 0.5 degrees of visual angle. Once the beginning of a fixation point had been established, subsequent POR points were cosidered as part of the fixation (and contributed to the calculated fixation duration and x/y location) if they fell within one degree of the current fixation point. PORs could deviate from (and contribute to the calculation of) the current fixation point by as much as 1.5 degrees, provided that at least one of two subsequent points fell within 1.0 degrees of the fixation point, and that the mean of the most recent three PORs fell within 1.0 degrees of the current fixation point. PORs falling beyond 1.5 degree boundary did not contribute to the calculated x/y position of the fixation point. The current fixation was terminated when the mean position of the most recent three PORs fell greater than 1.0 degrees from the current fixation point, or when a blink of greater than 200.0 msec was observed. From these data, the number of fixations per target was calculated on a trial by trial basis for every participant. Furthermore, the average fixation time for each trial was calculated.

RESULTS

Search time-per-target data were analyzed by a repeated measures mixed effects analysis of variance (ANOVA) procedure, with fixed effects of display configuration and symbol prominence within display configuration, and random effects of subject and specific target types within the display conditions. Because the design was unbalanced (by visual prominence within display type, and by the number of targets within each condition) a Satterthwaite approximation was used to calculate the denominator degrees of freedom (see Littell, Milliken, Stroup and Wolfinger, 1996, for review), and least squares means were used for comparison. While differences between overall display types were not significant ($F_{3,39} = 1.03, p > 0.05$) a significant symbology type within display configuration interaction ($F_{4,53} = 11.92, p < 0.001$), indicated significant search time-per-target differences among symbology categories within the four display coding schemes. The search time data are presented in Figure 2. Tests for specific differences among the least squares means (using a Tukey-Kramer adjusted t-test for multiple comparisons) indicated that the block-NATO symbols of the VCS3 method had significantly lower search times than the gray-NTDS symbols of the VCS1 scheme and the color-NTDS symbols of the VCS3 method, ($p < 0.01$). Search time-per-target differences between the gray-NTDS symbols of the VCS1 display and the color-NTDS symbols of the VCS1 display, as well as the color-NTDS symbols of the baseline display, approached significance, ($0.1 < p < 0.05$). A similar ANOVA on accuracy data yielded no main effects or interactions. Mean accuracy was near 100 percent for all conditions.

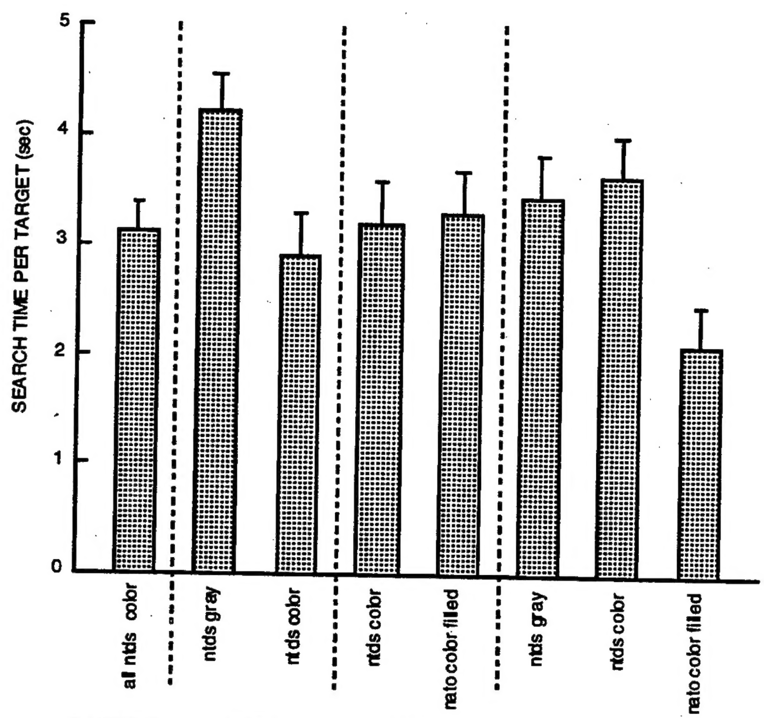


Figure 2. Mean search time per target(least squares means) as a function of symbol prominence for each display condition. Error bars represent one standard error of the mean.

The fixations-per-target data were analyzed by the linear model ANOVA procedure described previously. While mean differences between overall display types were not significant ($F_{3,39} = 0.23, p > 0.05$), a significant symbology type within display configuration interaction ($F_{4,53} = 11.20, p < 0.001$), indicated significant time-per-target differences among symbology categories within the four display coding schemes. The fixations-per-target data are presented in Figure 3. The Tukey-Kramer tests for differences among the least squares means revealed a pattern similar to that found for the time-per-target data: There were fewer fixations-per-target for the block-NATO symbols of the VCS3 method than for the gray-NTDS symbols of the VCS1 scheme and the color-NTDS symbols of the VCS3 method, ($p < 0.05$). An analysis of mean fixation times yielded no main effects or interactions. Mean fixation times for symbol sets within the display schemes (collapsed across specific symbol types within each set) ranged from 330 to 410 msec.

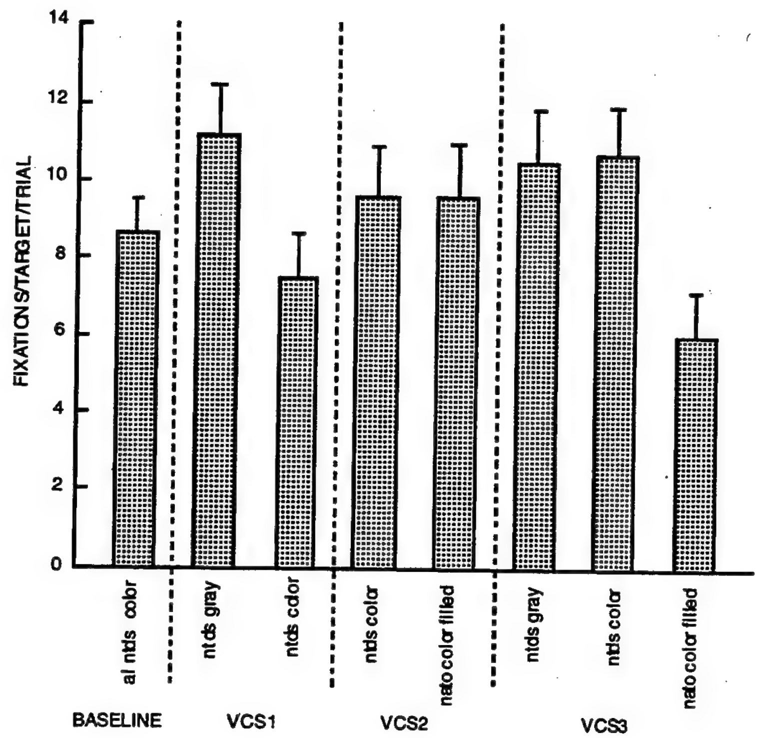
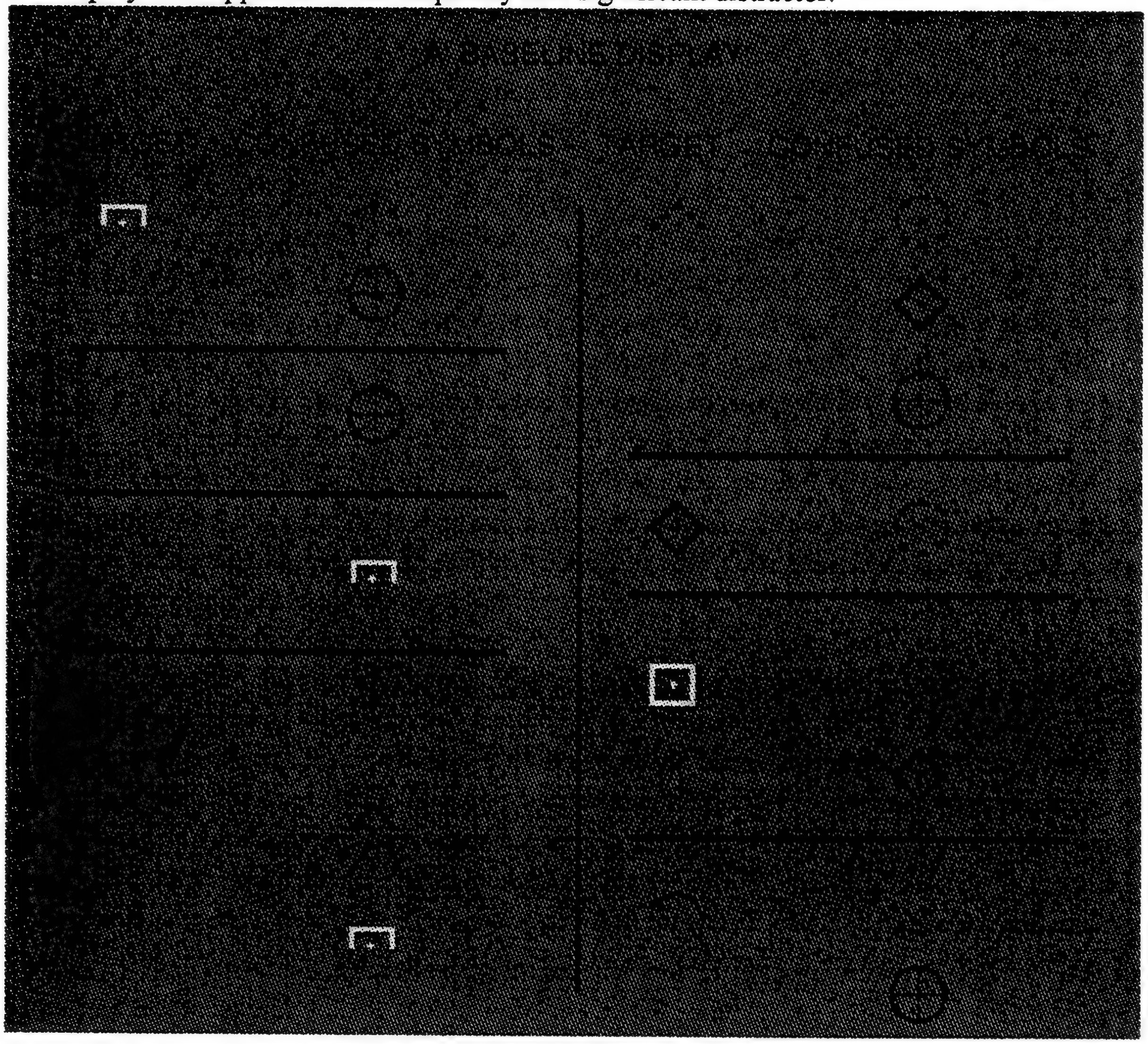
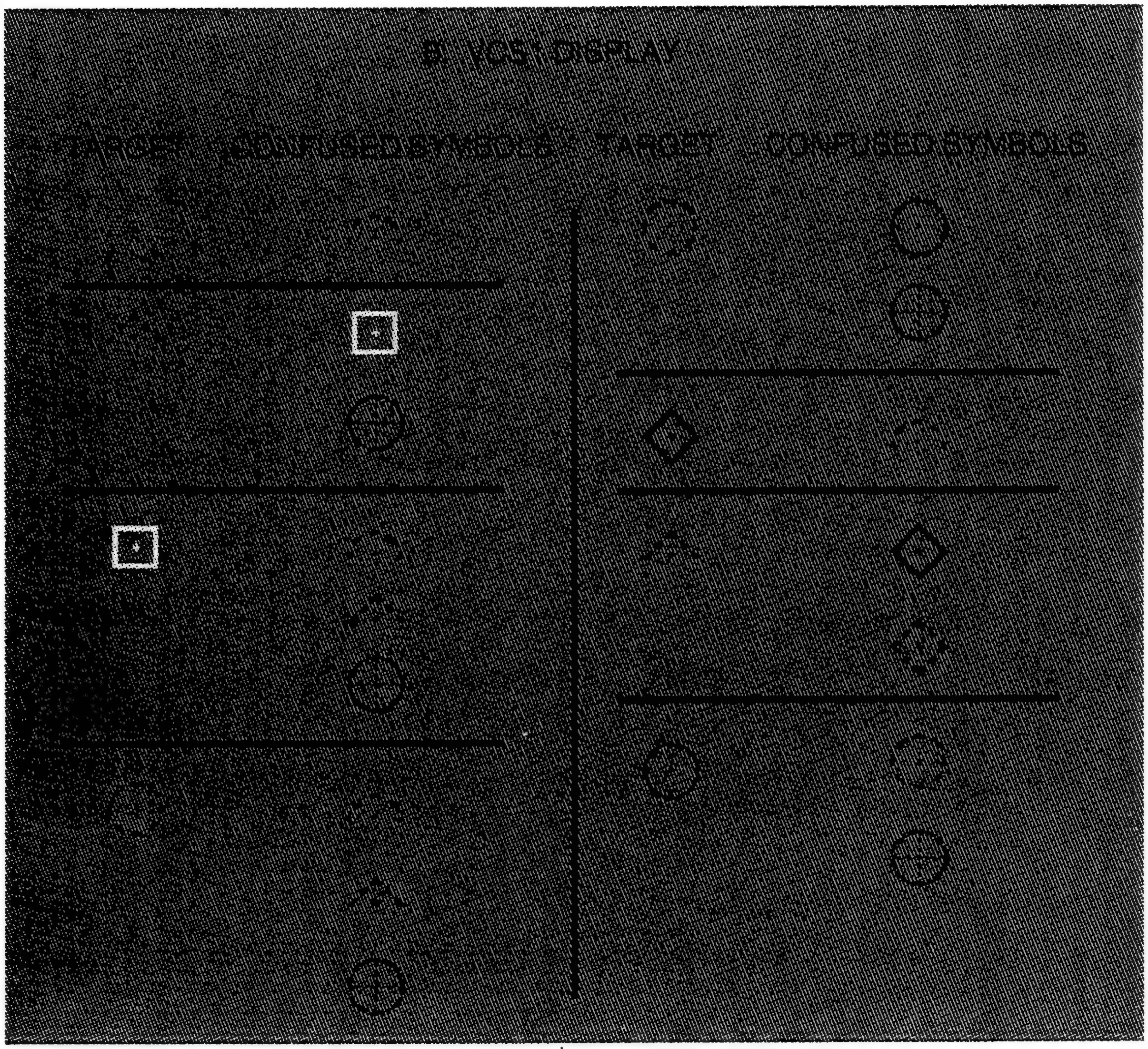


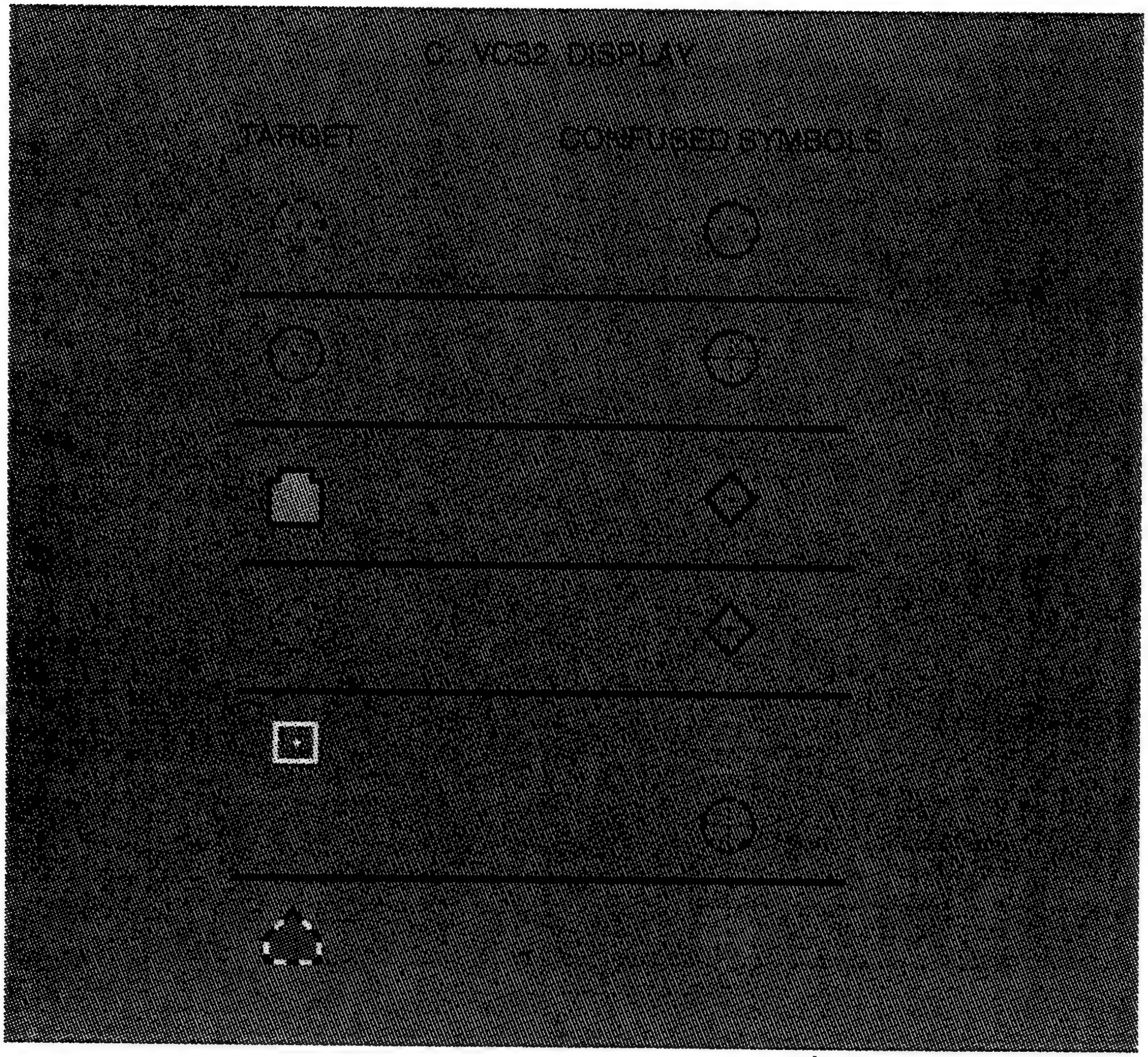
Figure 3. Mean number of fixations per target (least squares means) as a function of of symbol prominence for each display condition. Error bars represent one standard error of the mean.

Next, confusion matrices were constructed for each display condition to assess visual discriminability between specific symbols and groups of symbols. These matrices indicate which distractor symbols are fixated most during a search for a particular target. Visual inspection times for each display symbol were calculated by summing all fixation times falling within 1.25 inches (about three degrees of visual angle at a viewing distance of 57 cm) of a symbol. Inspection times associated with fixations falling within two or more symbol regions were divided evenly between

the corresponding symbols. Distractors were considered "significant" if the 95 percent confidence interval about their mean inspection times overlapped with the confidence interval for the mean inspection time for the target symbol. Furthermore, distractor symbols that were located within one inch of the target stimuli were not included in further analyses of confusability. Symbols meeting these criterion are shown in Figure 4 (A-D). Clearly some confusions are spurious, likely the result of symbol placement at locations where interim fixations are probable (developed further in the Discussion section), although several themes emerge from these data. First, the fewest confusions occurred in the VCS2 condition (color-NTDS and NATO symbols). This may be related to the preponderance of white and gray symbols found to be confused by the criterion described above: White and gray symbols accounted for 17, 63, 8, and 69 percent of the confused symbols within the baseline, VCS1, VCS2 and VCS3 display conditions, respectively. A second general finding involves tracks coded as *suspect* and *assumed friend*, which accounted for 39, 45, 23, and 27 percent of confused symbols within the baseline, VCS1, VCS2 and VCS3 display conditions, respectively. The *ownship* symbol appeared most frequently as a significant distractor.




B. VCS1 DISPLAY
TARGET
CONFUSED SYMBOLS
TARGET
CONFUSED SYMBOLS


C. VCS2 DISPLAY
TARGET
CONFUSED SYMBOLS

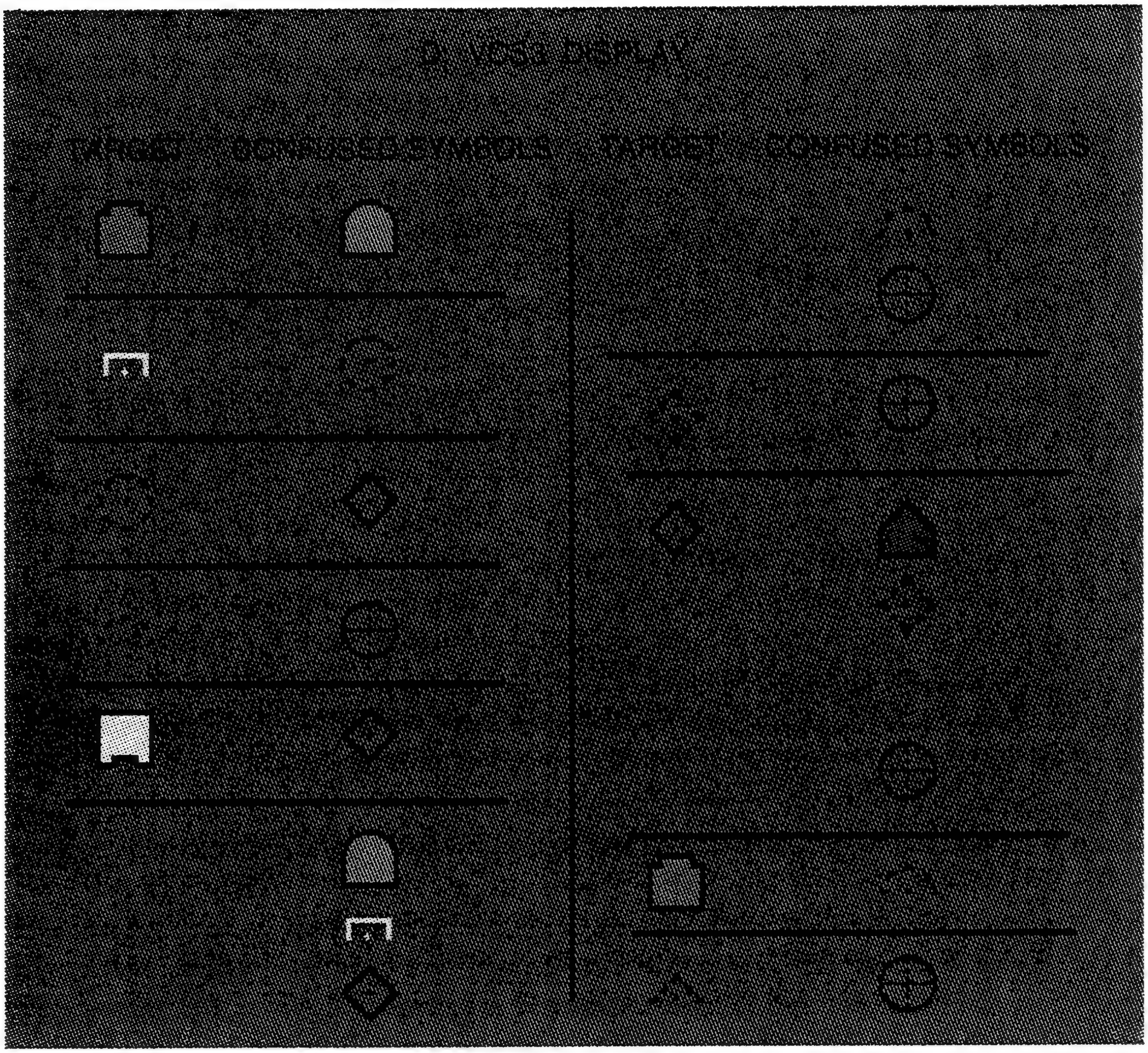


Figure 4. Target and distractor symbols from each display condition with similar visual inspection times.

DISCUSSION

The results of the present study partially replicated a methodologically identical study by Nugent (1996). Although we found no differences between the display schemes in general, the gray NTDS symbols of the VCS1 scheme had the slowest search rates. Also in aggreement with Nugent was the finding that the block-NATO symbols of the VCS3 scheme had the fastest search rates. In agreement with visual search data obtained by Zelinsky and Sheinberg (1997) the fixations-per-target data paralleled the search time data very closely (correlation of 0.95 for data in Figures 2 and 3). From these data we can draw the same conclusion as Nugent for symbol interactions: The use of gray NTDS symbols to define a subset of symbols (non-redundant with shape) in combination with color NTDS symbols is not recommended for tasks in which visual search for particular symbol types is required. The present data indicate that using standard color-coded NTDS symbols would be preferable to a VCS scheme defined by color and gray

NTDS symbols. The further analysis on eye activity data provides further insight into why this display condition stands apart from the others.

The confusion matrices indicate that particular classes of confusions are more evident in some VCS conditions, but must be interpreted in relative rather than absolute terms as some proportion of symbol confusions are likely spurious. Zelinsky, Rajesh, Hayhoe, and Ballard (1997) have demonstrated that on a fixation-to-fixation basis visual search proceeds to display areas of greater target likelihood. Fixation waypoints can fall within intermediate areas or upon non-target symbols by chance while attention guides fixations to display areas more likely to contain a target.

In the display configurations used in the present experiment, some non-target symbols may have been located in areas more likely used as fixation waypoints during search for target symbols, and thus had visual inspection times meeting the criteria for confusion with target symbols. Given these caveats concerning fixation waypoints the general findings clearly indicate that some symbol combinations yield more efficient search than others.

The VCS1 scheme (gray and color-NTDS symbols) contained the greatest number of confused symbols, while the VCS2 scheme had the fewest. The results indicate that the extent of confusions seems to be related to the number of gray and white symbols present in the display. Gray and white symbols, while clearly distinguishable at attentive levels, may not produce efficient pre-attentive grouping during effortful searches on shape. Unlike more distinctly colored stimuli, it is conceivable that overt attention may be required during search to differentiate gray from white symbols that are similar in shape, producing longer search times and a greater number of fixations. Furthermore, research on suprathreshold visual performance by Rea and Ouellette (1988, 1991) has shown that luminance contrast, retinal illumination, and target size interact to determine performance efficiency. Line-drawn symbols, by virtue of their spatial extent, are influenced to a greater extent by symbol/background contrast levels. While the VCS scheme using subdued gray symbols was suitably designed for higher level task organization purposes, combined use of gray and white symbols results in relatively inefficient performance under dynamic search conditions. Alternatively, the VCS2 scheme (color NTDS and color NATO) contains more distinct colors (enabling pre-attentive grouping) *and* disparate shapes (line-drawn and block filled), permitting efficient search after filtering for color.

A second design issue can be garnered from the finding that suspect and assumed friend tracks are evident in a disproportionate number of symbol confusions. These symbols are designed to indicate only partial membership in a given category and contain a dashed border around the periphery of the symbol. Although conjecture, it is likely that the peripheral pattern of these symbols produces power at spatial high spatial frequencies that overlap with power spectra of many other candidate target symbols, requiring overt attention (and fixation) during the search process. Suspect and assumed symbols are necessarily coded to attract attention because they are often tactically important. However designers need to understand that these symbols add disproportionate amounts of visual noise and clutter to tactical diplays when coded in the manner described above.

Finally, the present data were not consistent with previous research by Laxar and Van Orden (1994) and Van Orden and DiVita (1996) who found search times for block-filled NATO symbols to be longer than for NTDS symbols. Their paradigms required subjects to respond to

the presence or absence of a target symbol within an array of distractors that changed from trial to trial. This "traditional visual search procedure" has been routinely used in the psychological literature for years (e.g., see Triesman, 1986; Wolfe, 1992). As discussed by Van Orden (1998), the disparate results may have to do with a methodological confound: Compared to line-drawn symbols, the block filled symbols may contain spatial frequencies that produce large transients and/or group to form a global pattern when simultaneously presented in the regularly-spaced 42 item stimulus arrays used in the studies. This method could result in a pattern-masking effect for some brief period at the onset of each trial. The search and tagging method used by Van Orden and Lauben (1991) and the present study would not contain such an artifact, as the stimulus screen did not change after each trial. Moreover, the search and tagging method used in the latter two studies has greater external validity with shipboard console track selection procedures.

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13. ABSTRACT ***(Maximum 200 words)***
Combining different tactical display symbols within a single display has been shown to be an effective way of organizing a display for particular command and control tasks. Previous results have shown that some variable coded symbol (VCS) combinations result in poorer visual search performance and negative user opinion data. The present study examined four different tactical display symbol schemes using a visual search procedure and simultaneous collection of eye fixation data. These conditions included a baseline condition composed of color-coded and line drawn NTDS symbols, a combination of recessed gray NTDS and color-coded NTDS symbols (VCS1), a combination of color-coded NTDS and block-filled, color-coded NATO symbols (VCS2), and a combination of all three of the aforementioned symbol types in one display (VCS3). Nine subjects completed a search and selection task containing four blocks and a total of 168 targets. The recessed gray NTDS symbols of the VCS1 scheme demonstrated the most prolonged search times, while search times were fastest for the color-filled NATO symbols of the VCS3 scheme. Target-distractor symbol confusions, as determined by fixation dwell times, were least evident in the VCS2 configuration. Gray and white symbols accounted for a disproportionate percentage of symbol confusions across all display conditions. The use of recessed gray and prominent color-coded line-drawn (NTDS) symbols as a VCS tactical display scheme is not recommended. Combining color-coded NTDS symbols with prominent block-filled color NATO symbols is associated with faster visual search rates and fewer target/distractor confusions.

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